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14. ABSTRACT

The fusion of real-time remote sensing imagery with numerical ocean circulation models provides a unique capability for monitoring the coastal ocean. A real-time ocean monitoring system is currently operating in the Gulf of Mexico. Dynamic changes in the ocean environment occur on scales of hours, days, weeks and years, which influence biological, ecological and physical processes. By monitoring these processes at different spatial resolutions, new enhanced capability is available to coastal managers and researchers for making decisions. Monitoring of physical processes and bio-optical responses are currently being done for the Gulf of Mexico. Open ocean eddies and loop current interact with coastal processes such as river plumes and tides and have significant impact on the biological and ecological processes along our shores. Until now we had no capability to routinely monitor these ocean conditions without insitu sensors and observations. Now the "weather" in the Gulf of Mexico is being monitored daily and provides coastal managers and researchers an edge in tracking or pin-pointing events. This information assists the decision maker in identifying how physical events are influencing the coastal ecosystem.

15. SUBJECT TERMS
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"Ocean Weather" in the Gulf of Mexico: Exploiting Real-Time Satellite Ecological Properties and Circulation Models for Coastal Ocean Monitoring

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ABSTRACT- **The fusion of real-time remote sensing imagery with numerical ocean circulation models provides a unique capability for monitoring the coastal ocean. A real-time ocean monitoring system is currently operating in the Gulf of Mexico. Dynamic changes in the ocean environment occur on scales of hours, days, weeks and years, which influence biological, ecological and physical processes. By monitoring these processes at different spatial resolutions, new enhanced capability is available to coastal managers and researchers for making decisions.**

Monitoring of physical processes and bio-optical responses are currently being done for the Gulf of Mexico. Open ocean eddies and loop current interact with coastal processes such as river plumes and tides and have significant impact on the biological and ecological processes along our shores. Until now we had no capability to routinely monitor these ocean conditions without insitu sensors and observations. Now the "weather" in the Gulf of Mexico is being monitored daily and provides coastal managers and researchers an edge in tracking or pin-pointing events. This information assists the decision maker in identifying how physical events are influencing the coastal ecosystem.

How is this being done? Improved bio-optical algorithms have been developed and applied to ocean color satellite imagery from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) providing estimates of water constituents such as absorption properties from phytoplankton, color dissolved organic matter (CDOM), and detritus and backscattering properties related to sediment concentration. In addition, advances in numerical circulation modeling (Navy Coastal Ocean Model – NCOM) provide nowcasts and forecasts of coastal processes (currents, sea surface height, salinity and temperature). Physical ocean properties of temperature, salinity, and currents from NCOM are combined with daily latest pixel composite products of phytoplankton, CDOM, and detritus absorption, backscattering and sea surface temperature (SST). We demonstrate an advanced environmental monitoring capability available operationally that highlights the fusion of physical (model) and bio-optical properties (satellite).

The entire Gulf conditions are demonstrated daily in addition to higher resolution monitoring of coastal conditions. We will focus on Mississippi and Louisiana Coast using high resolution (250 meter resolution) MODIS imagery. We will demonstrate a capability of supporting coastal manager's and researchers integrating satellite bio-optical products, model circulation (current vectors), sea surface height (contours), salinity (contours) and temperature (contours) layers into Google Earth. In addition, we will demonstrate promising new research using satellite optics and numerical models to create surface optical forecast (hourly increments up to 48 hours) and a 3-D optical volume of the ocean derived from a physical (model) / optical (satellite) Gaussian relationship optimized using insitu profiles. By using these methods of fusing the satellite and ocean circulation model it will provide coastal zone managers with a new capability to assess, predict and track Harmful Algal Blooms, Hypoxia, and sediment discharge.

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I. INTRODUCTION

Satellite ocean color and SST have extended beyond the simple capability of viewing imagery. We now have the capability of merging satellite imagery with physical models to provide a new capability to understanding and predicting the ocean environment. Coastal management needs a capability to monitor and predict conditions along our coastal lines. This requires multiple assets including satellites, models and insitu observations. We have constructed a real-time monitoring and prediction system based on fusing multiple satellites (SeaWiFs, MODIS, MERIS) with physical models and observations. This real time capability updates daily on the web giving us the current state of the Gulf of Mexico. The real-time capability has been operating in the Gulf of Mexico for the last 5 years as part of the NASA funded projects, The NASA Research, Education, and Applications Solutions Network (REASoN) "Sensor to User – NASA Data for Coastal Zone Management Applications Developed from Integrated Analyses", to demonstrate the uses of NASA satellite products combined with data-assimilating ocean models to provide *near real-time information* to maritime users and coastal managers of the Gulf of Mexico. The primary goal of this collaborative effort is to provide an end-to-end pipeline -- from data acquisition to creation of information for decision making – of coastal products for diverse user communities.

NRLSSC provides state-of-the-art oceanographic modeling and satellite product development for the identification and forecasting of ocean phenomena. The improved data products and architecture created through this project are extended to operational users, such as the National Oceanic and Atmospheric Administration (NOAA), for enhanced decision-making capabilities for monitoring, assessing, and predicting the coastal environment. The REASoN collaboration between government agencies advance a new capacity to assemble integrated ocean data products and newly developed ocean data products and to provide these products to coastal managers.

We have recently expanded this capability to include bio-optical forecasts and 3-D bio-optical structures or volumes. The objective of this paper is to demonstrate our present capability in a real time Gulf of Mexico ocean weather capability. The real time conditions are available daily through several sources both at NRL and NOAA bringing new capabilities to linking the optimum satellite and physical models.

II. COASTAL REMOTE SENSING AND MODELING

A. SATELLITE PROCESSING AND PRODUCTS

Ocean color satellites and the ability to detect biological, geological, and optical processes within ocean waters have advanced significantly in the last five years. Research has demonstrated the capability to uncouple the water signature into its fundamental components using spectro-photometric methods [1,2]. The ability to resolve these properties has extended the utility of these satellite platforms beyond research applications.

.NRLSSC processes real-time satellite data from a number of satellites for selected regions using the Automated Processing System (APS) developed at NRLSSC. These satellites are limited by cloud cover and to the near surface values. The basis for characterizing the ocean environmental conditions in the Gulf of Mexico arises from the number of satellites processed at NRL (Table 1).

Table 1. Ocean Color and Thermal satellites processed at NRL

. Product	Application
AVHRR (Thermal)	Sea Surface Temperature and Beam Attenuation (Turbidity)
SeaWiFS (Ocean Color)	Spectral Backscattering (Sediment Loads), Spectral Absorption, Color Dissolved Organic Matter (CDOM), Spectral Particle Absorption, Spectral Phytoplankton Absorption, Spectral Remote Sensing Reflectance, Attenuation Coefficients, Aerosol Concentration, Beam Attenuation Coefficient, Swimmer Visibility (Horizontal and Vertical)
MODIS (Ocean Color)	Spectral Backscattering (Sediment Loads), Spectral Absorption, Color Dissolved Organic Matter (CDOM), Spectral Particle Absorption, Spectral Phytoplankton Absorption, Spectral Remote Sensing Reflectance, Attenuation Coefficients, Aerosol

NRLSSC processes level 1 SeaWIFS, MODIS and MERIS data at 1 kilometer resolution. Currently, individual satellite images are processed into quantitative products for ocean and coastal monitoring (Table 1). New advanced algorithms have been developed for ocean color sensors for the last eight years and have developed extensive algorithms to deconvolve ocean color spectral signatures into optical components. Advances using 1 kilometer, 500m and 250m channels from the MODIS sensors have proved new spatial resolution (250m) products [3]. We now have the ability to monitor estuaries and embayments such as Mobile Bay and Tampa Bay. The robustness of these algorithms insures their applicability to future satellites.

Table 2. Products and associated applications derived from NASA and other satellite sensors.

Product	Application
Chlorophyll concentrations	Biological processes; algal bloom identification
Spectral backscattering	Particle concentration, composition (organic and inorganic), resuspension
Spectral absorption	Total absorption from inorganic material, phytoplankton, pure water, particulate and dissolved components; indicative of changes in water quality
Colored dissolved organic matter (CDOM)	Tracer of terrigenous or marine organic material; conservative relationship with salinity in river plumes; indicative of photo-oxidation processes
Spectral particle absorption	Particle composition (organic vs. inorganic)
Spectral phytoplankton absorption	Linked to pigment packaging effects within phytoplankton cells
Remote sensing reflectance	Absolute water color
Attenuation coefficient (k532)	Light penetration depth; light availability at depth
Aerosol concentration	Atmospheric visibility; atmospheric correction for satellite imagery
Beam attenuation coefficient	Total light attenuation
Swimmer visibility	Horizontal viewing near sea surface
Sea surface temperature (SST)	Skin temperature

B. COASTAL CIRCULATION MODELS

Ocean circulation models have advanced significantly for the Gulf of Mexico. The Navy Coastal Ocean Model (NCOM) developed at NRLSSC [4,5,6]. This model is a state-of-the-art numerical ocean forecasting system. NCOM is a data-assimilating model with input received from both daily SST and altimeter-derived sea surface height (SSH). NCOM operates as part of the Intra-Americas Seas Nowcast / Forecast System (IASNFS), which runs daily for the Gulf of Mexico to generate a 0 - 48 hour forecast at 41 vertical sigma-z levels. Analyzed and predicted variables in four dimensions include a time series of SSH, temperature, salinity, and currents (Fig. 1). Model forcing includes winds and surface fluxes from the Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS), eight tidal constituents, and river and coastal drainage flows.

C. MERGING SATELLITE PRODUCTS AND CIRCULATION PRODUCTS

The satellite and numerical model data feeds are brought together daily to form animations of ocean conditions in the Gulf of Mexico. This independent product fusion provides new potential for monitoring the coastal ocean. Satellite imagery alone is often not adequate to monitor ocean conditions. Information added from a modeling context allows the user to better understand the satellite imagery and the phenomena depicted (Fig. 2). A major focus of this project is to provide a real-time, long-term data stream, which with data fusion and display enhancements, provides a monitoring capability for making coastal decisions. This project was designed to help coastal managers effectively *use* these combined satellite and ocean model products for decision processes. This extends beyond just making the data available and requires direct interaction with the users in order to provide an integrated product.

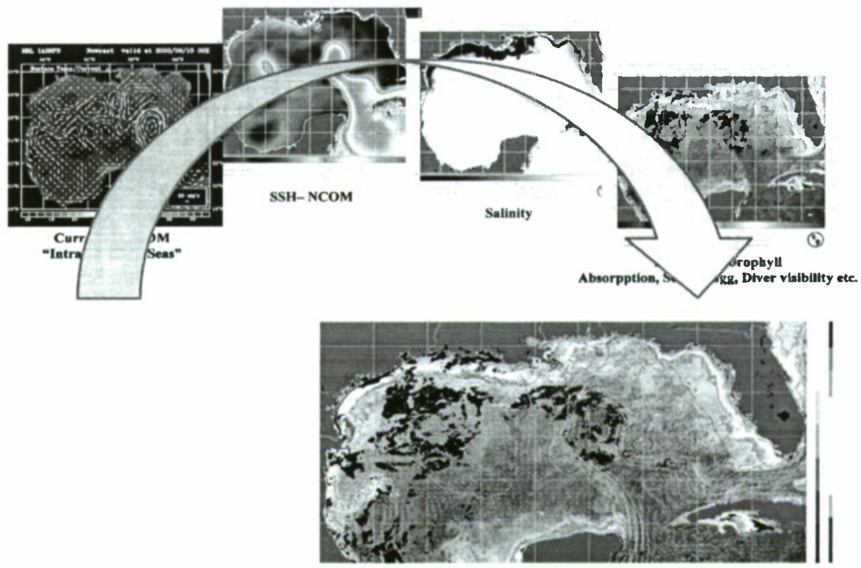

Fig. 1: The fusion of the IASNFS and the MODIS products provides a realistic representation of today's "ocean weather". A fused product is created by combining ocean properties from ocean models and satellite imagery; from this technique, features such as surface currents, sea surface height, salinity, and chlorophyll can be displayed in one scene. The satellite represents the 7 day latest pixel display with black area identifying void chlorophyll retrievals in the last week. These image/ model products are produced daily.

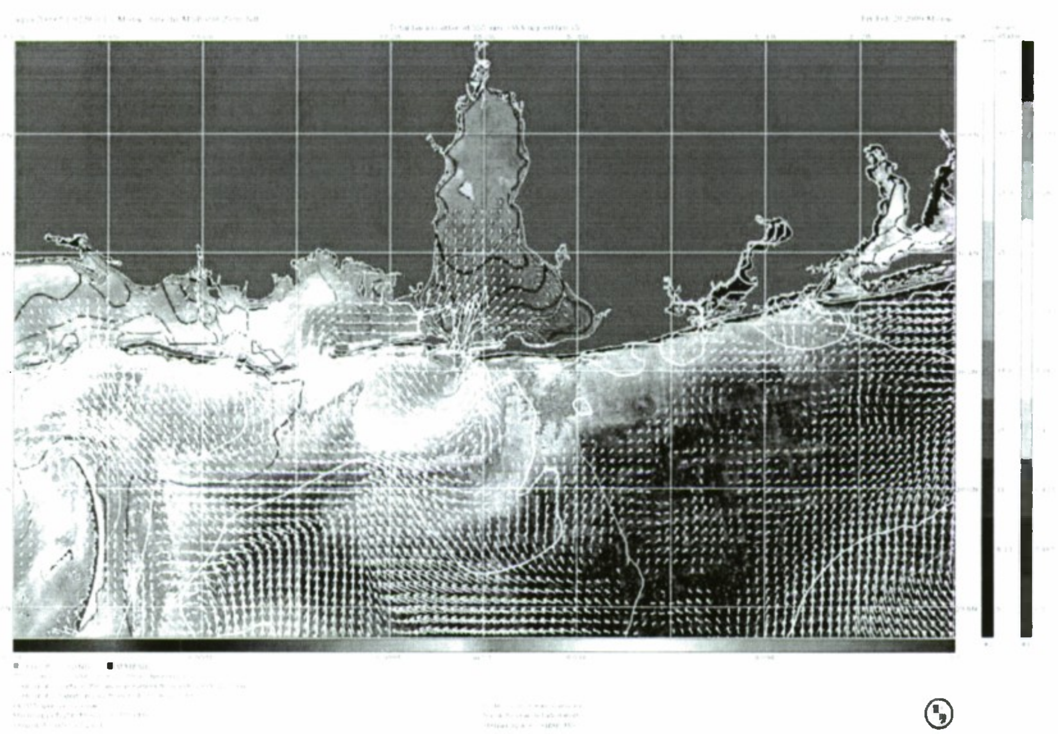

Fig. 2: The fusion of the NGOMNFS (IASNFS Nest) and MODIS Aqua 250m backscattering at 555nm (measure of the water's particle concentration) products for February 20, 2009 provides a realistic representation of the days "ocean weather". Model overlays include surface current vectors (white), Sea Surface Height contours (colored) and Sea Surface Salinity contours (BW).

D. GOOGLE EARTH DATA VISUALIZATION

The data visualization is made available using the daily monitoring satellite and models into Google Earth. This daily monitoring and forecast capability is easily displayed and animated in Google Earth providing coastal managers a capability to define the latest conditions in the Gulf of Mexico. The data is made available at http://cobalt.nrlssc.navy.mil:8000/index.html. The data is also made available through the NCDDC web page for use with the DMR, NMFS and Harmful Algal Bloom GIS web portals.

Fig. 3. Google Earth example of MODIS Aqua backscattering at 551nm acquired on May 26, 2009. Model contours (sea surface height) and vectors (currents) are available for overlay as separate layers. The modeled parameters and additional satellite parameters can be toggled on and off.

E. FORECASTING SATELLITE SURFACE BIO-OPTICAL PROPERTIES

A new capability has been developed to predict the satellite ocean color products. By combining forecast ocean physical models with today's satellite products such as chlorophyll or backscattering we have a new decision making product. Coastal managers now have a capability for a forecast of the ocean ecosystem based on today's satellite image. The bio-optical products from the satellite ocean color are advected using the physical 3-D surface currents (upper 3 meters) to provide a forecast of the satellite optical products using a Eularian advection scheme. An initialization image (Seed) is formed daily in which the best known bio-optical properties for that day are composited using a combination of the 7 day latest pixel composite image, 24 hour forecast from the previous day and interpolation techniques [7]. Today's imagery is used to forecast tomorrow's ecosystem surface properties. An near real time validation of the products is determined on a daily basis by comparing the forecast with the next days satellite image. Although the validation is done the next day, the quality of the forecast can be determined daily.

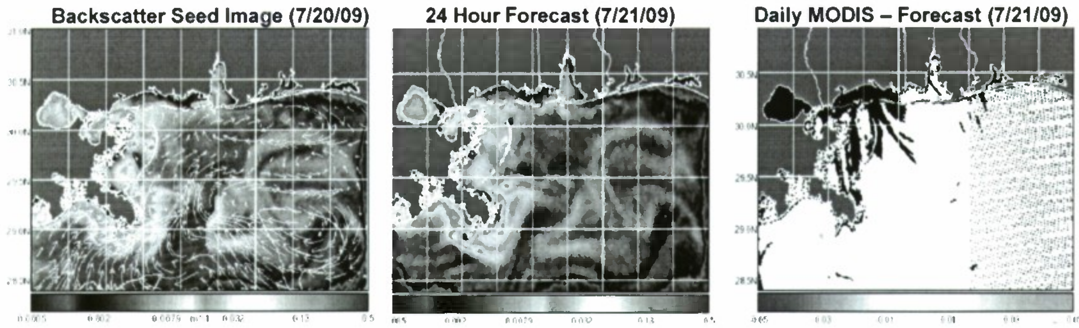

Fig. 4. (A) The MODIS Aqua seed image from July 20, 2009 with modeled currents and sea surface height overlaid. (B) 24 hour optical forecast of backscattering (1/m) of the Mississippi Bight region for July 21, 2009. (C) The difference between the actual MODIS-Aqua image acquired on July 21, 2009 and the 24 hour forecast from July 20, 2009.

F. 3-D OPTICAL VOLUME

Another new capability is presently being developed at NRL to extend the satellite surface optical properties to a 3-D volume using a combination of the vertical structure from the physical models to determine the Mixed Layer Depth (MLD) with the surface satellite optics and insitu data for optimizing the 3-D model. This procedure [8,9] examines the relationship of the physical and bio-optical vertical properties and uses optimization to couple the physical vertical structure with the satellite bio-optical properties through a Gaussian relationship. This 3d approach determines the optimum coupling relationship between the physical vertical properties (mixed layer depth, and the intensity of the mixed layer) with the vertical bio-optical layers (chlorophyll maximum). The locations of the subsurface layers are constrained by the MLD, 1% light level and the surface chlorophyll properties.

The optimization of the physical – biological layers is performed based on a set of 4 equations which are used to parameterize the Gaussian profiles [10]. The depth of the chlorophyll max (Zm) is constrained between the MLD and the 1% light level (PD) and the intensity of the mixed layer depth (IMLD) using the equation:

$$\mathrm{Zm} = ff(\,\mathrm{MLD} + (\mathrm{PD} - \mathrm{MLD}) * e^{(-\mathbf{C1} * \mathrm{IMLD})}\,) \qquad (1)$$

Similarly the Chlorophyll Maximum for the profiles is estimated by:

$$\mathrm{Chl\text{-}Max} = ff(\,\mathrm{MLD} / \mathrm{PD} * \mathbf{C2}/\mathrm{SfcChl}) \qquad (2)$$

The Gaussian Spread is estimated using:

$$\sigma = f(\,(\mathbf{C3}-1) * \mathrm{EXP}(-\mathbf{C4} * \mathrm{IMLD}\,) + 1\,) \qquad (3)$$

The coefficients C1, C2, C3, andC4 are obtained from optimization based on insitu data. These physical –biological relationships are developed based on insitu data profiles and than extended beyond the insitu data locations to a broader region by applying these relationships to the domains of the physical models and satellite ocean chlorophyll imagery. The approach allows the satellite surface layers to be extended to the vertical volume. The 3d biological volume provide a new capability to coastal managers to characterize the subsurface biological properties which may be outside the view of the surface satellite. Although still in a research mode, these 3d bio-optical fields are presently being tested and evaluated in navy operations for determining the effect use of underwater imaging systems. An example of the 3d volume for the Mississippi Delta is illustrated in Fig. 5.

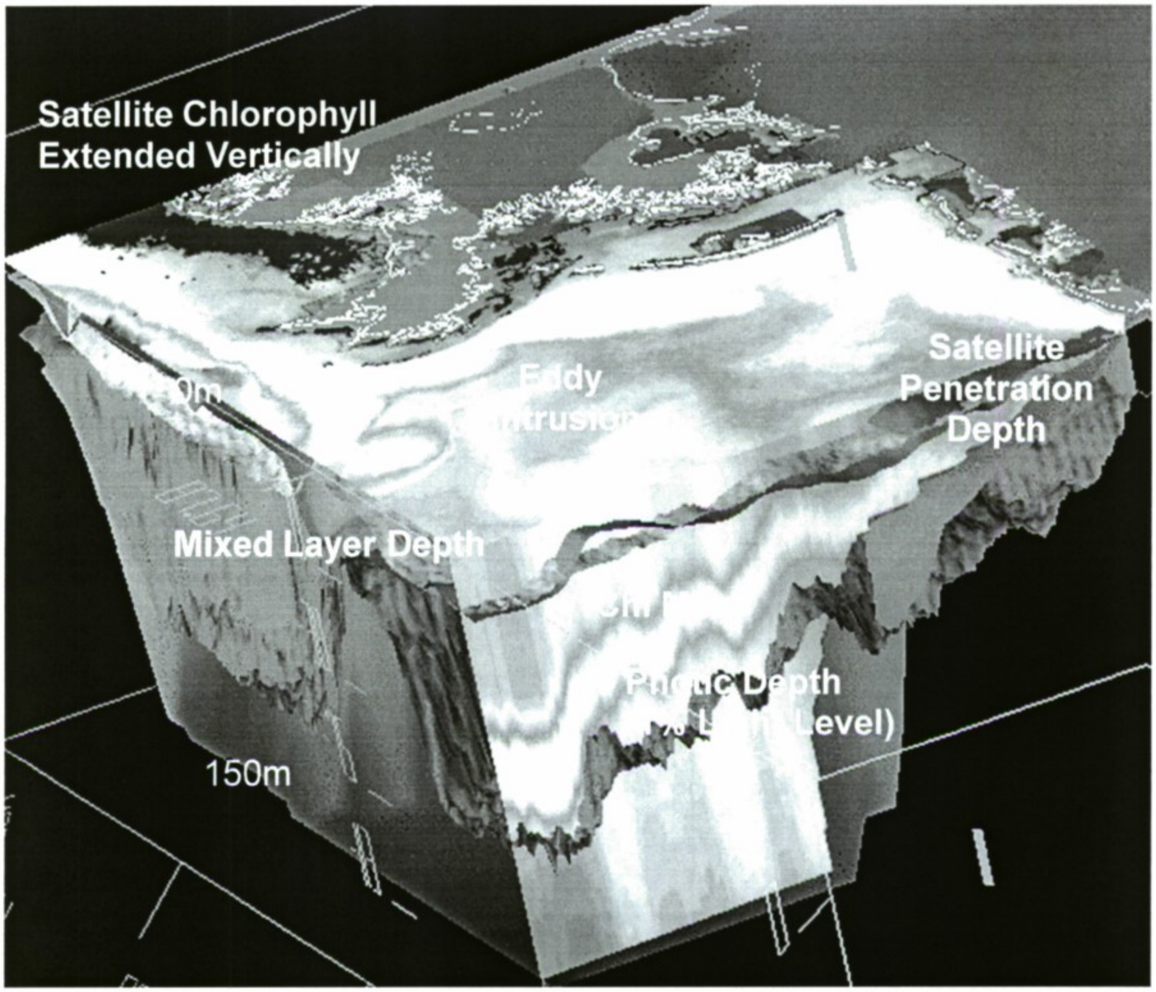

Fig. 5. 3-Dimensional optical volume generated for May 6, 2004. Note that the subsurface chlorophyll max is located between the Mixed Layer Depth and 1% light level / photic depth. Bathymetry is clipped at 150m.

III. SUMMARY AND CONCLUSION

Being able to use fuse real-time satellite surface bio-optical properties with numerical model physical properties provides a new approach toward characterizing the ocean weather in the Gulf of Mexico. New and more advanced capabilities to monitor the ocean conditions now and into the future will make decision making timelier. The ability to monitor estuary, coastal embayments and open ocean properties at different spatial resolutions is available and very important for coastal managers and researchers to make decisions that will affect the community and economy. Monitoring of physical processes and the response of bio-optics to these processes can assist and advance the decision making process. It is very important to know when and how certain offshore features such as surface and subsurface rings and eddies interact with river outflows and coastal regions and how it affects the coastal water quality and species. Present and future capability will allow afford decision makers the luxury of knowing when harmful species form and where they will be tomorrow, the water column becomes oxygen depleted, following river outflows with heavy sediment loads and contaminants, etc.

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